

Area Preserving Dynamic Geospatial Visualization on Physical Globe

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Abstract: We present a methodology for creating dynamic visualization of geospatial data on physical globe. To achieve this goal, we use a piecewise curved-display and multi-projector setup. The curved-display is a physical representation of the globe and provides closer approximation of the Earth and reduce distortions. In our method, we use a Discrete Grid Global System (DGGS) for discretizing the Earth to hierarchical cells in different resolutions. This DGGS employs an area preserving projection for on the fly integration of geospatial datasets. There is a one-to-one correspondence between pieces of our curved-display and DGGS cells in a specific resolution. We use 3D printing technology for fabricating of each piece of the display. For controlling the projection, we developed software that takes data from DGGS, warp it and then feeds it to the projectors. The fabrication of the cells and the generation of projection feed follow the same structure of DGGS. We demonstrate the flexibility of our construction with several example setups and apply them to visualize multiple datasets, including time-varying geospatial data.

1 INTRODUCTION

As the only livable planet for human beings, the Earth is important and knowing different aspects of this huge and live organism helps us in our critical decision-making. Since the recent advancement of geospatial sensors has resulted in several technologies for collecting data (e.g. satellites, smart phones, meteorological instruments, and LIDAR), today we are faced with the explosion of the volume and variability of geospatial data. An important challenge is how to integrate and process this huge dynamic dataset. This challenge has been tackled by GIS and recently Digital Earth systems (Mahdavi-Amiri et al., 2015a). However, another important challenge, is visualizing this large and dynamic dataset to help the general public understand and analyse our live planet and make decisions about the Earth.

The common approach for geospatial visualization in GIS is to project Earth-related dataset onto 2D display screens using projection methods like Mercator (Graffarend, 1995). However, projecting geospatial information from the surface of the Earth to 2D maps creates some issues. Problems such as unwanted distortion of 2D maps, misinterpretation of the size of the areas (e.g. countries), and relative positions are just few of the challenges (Mahdavi-Amiri et al., 2015a; Zolfaghari, 2014; Snyder, 1997). In section 4 we

will demonstrate the misinterpretation in visual analysis resulting from the area distortion of Mercator mapping (See Figure 16).

In Digital Earth systems (e.g. Google Earth), geospatial datasets are mapped on a 3D globe which can conceptually reduce distortions (See Figure 17). Well-thought interactive interfaces could provide users with a better understanding of a 3D globe resulting from an exploratory experience. However, to create the 3D globe, it is necessary to define a mapping (commonly Mercator) from 2D domain to the surface of the Earth. In addition to perspective distortion, this mapping also creates some kind of distortion (i.e. area, shape and distance).

One possible solution for reducing the map distortions is to use a 3D physical globe, as a medium for presenting geospatial datasets (Meng, 2003; Hruby et al., 2008). The idea of physical visualization of geospatial datasets has been recently explored in (Djavaherpour et al., 2017). The physical globe can prevent some misconceptions and inaccuracies commonly found in 2D maps. Unfortunately, in this scenario the data and globe are physically fixed and the visualization is static; it would be much better if it was possible to present vividly *dynamic and live* data on this physical model. Inspired by spherical displays (Vega et al., 2014), we introduce a flexible and scalable method for accurate (i.e. area preserving)

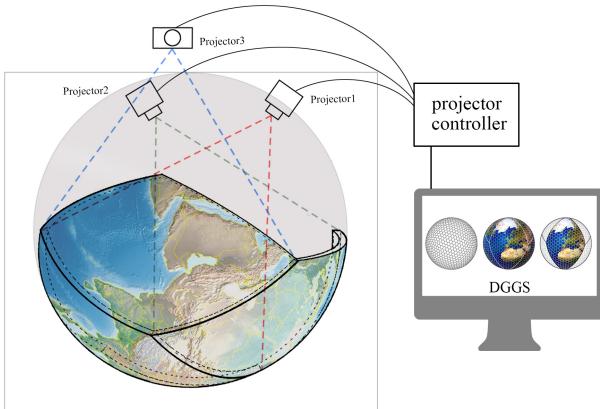


Figure 1: Area-preserving dynamic geospatial visualization on curved display.

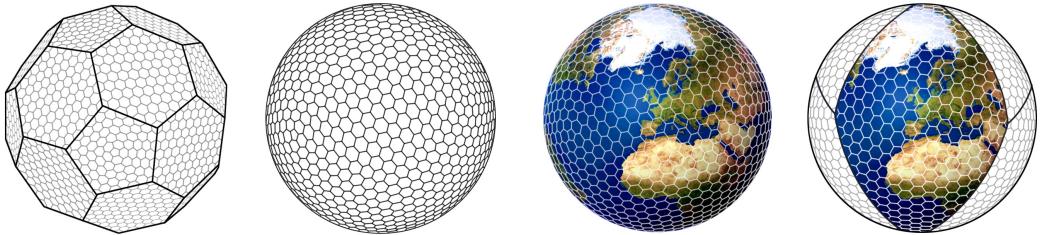


Figure 2: The resulting flat cells are then mapped to a sphere/ellipsoid using the inverse of a projection.

projection of static or dynamic geospatial datasets. In our method, we use a hierarchical grid system for discretizing the Earth surface to regular (i.e. size and shape) cells. We use the geometry of these curved cells for creating a curved display panel (See Figure 1). Further, we use multiple projectors to feed live geospatial data to the curved display. The associated dataset for each cell is rendered as an image and carefully projected on the surface of our curved display. To do this, we developed a projector controller which takes the geometry of curved cells, the associated data images and the projector (device's) parameters. Based on this information, the projector controller prepares and adjusts the input data images for the projector device.

Using curved-displays, we can achieve a better approximation of the Earth that reduces the area and shape distortions necessary on standard 2D displays. To create the curved-display and projector setup, it is important to define an accurate correspondence between regions on the Earth and areas on the curved-display. For example, to have an accurate analysis on the global warming issue on a region close to the north pole, the average and projected temperatures of

that region must be mapped to an area on the curved-display which has a proportionally right location with the same area.

To accurately represent data within our model we rely on a discretization of the surface of the Earth into cells. The size of cells should be defined according to the desired scale and accuracy of the curved-display. By making use of a hierarchical tessellation of the Earth, such as a Discrete Global Grid System (DGGS) method (Mahdavi-Amiri et al., 2015a; Purss et al., 2016; Sahr et al., 2003; Xie et al., 2013; Randall et al., 2002), transitions between scales and accuracy can be easily achieved. In DGGS, the Earth's surface is approximated by a convex polyhedron. Depending on the desired accuracy, each face of the polyhedron is refined to generate a hierarchy of regular flat cells on each face. The resulting flat cells are then mapped to a sphere/ellipsoid using inverse of projections, preferably area preserving (see Figure 2). The resulting hierarchical cells are indexed and used for addressing geospatial datasets. There are several active DGGSs used for creating Digital Earth systems (Mahdavi-Amiri et al., 2015a). In these systems, large amounts of live geospatial datasets are assigned to the DGGS

cells. The current version of Google Earth also uses DGGS, but unfortunately, its projection is not area preserving.

For this work, we use Pyxis' (Mahdavi-Amiri et al., 2015b; Peterson, 2006; Sherlock et al., 2016) Digital Earth system. The system is based on Aperture 3 hexagonal grid system and the Snyder area preserving projection (Snyder, 1992). For the purposes of data exchange and transmission, hexagons are aggregated and converted to rhombus cells (see Figure 2). We use these rhombus cells for constructing our curved-display.

In our method (see Figure 1), we visualize geospatial DGGS on a piecewise curved-display. The idea is to use multiple projectors, each of which is dedicated to one or more rhombus cells. To use the indexed data on DGGS, we use the same cell structure for constructing the curved-display. We have constructed this piecewise curved-display by 3D printing the DGGS model's rhombus cells, and present our technique for this entire work-flow.

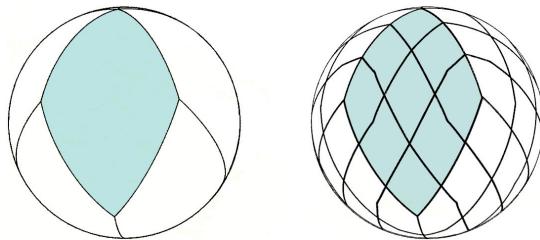


Figure 3: Each panel represents one tenth of the surface of the globe. Left: resolution zero (coarsest resolution). Right: resolution one (one level of refinement).

The main contribution of this paper is introducing a method for accurate (area preserving) visualization of dynamic geospatial datasets through a framework for constructing curved-display. Our method is based on DGGS which provides great flexibility and scalability which is not available in the spherical display proposed previously. For example, with our approach we can have an installation with one or multiple panels at any desired resolution and size, each of which is associated to a physical place on the Earth. Using 3D printers, we can easily fabricate a frame for each panel and then attach them to form curved panels, which are covered by projection paper. Panels can be used in assembled form or disjointed form, to compare distant regions of the Earth, side by side (See Section 4).

The remainder of this paper is structured as follows. In Section 2, we provide a short review of works related to visualization of geospatial data and curved-display projection. Section 3 is dedicated to the methodology of the introduced framework, which is

organized into three sections: curved-display screen, setup of the installation, and projection onto the Earth model. Further, we present some results of the installation in Section 4. We then discuss the possible directions that this framework can go as future works in Section 5.

2 RELATED WORK

In addition to the related papers discussed in the introduction, in this section, some of the related papers in the areas of geospatial visualization and curved/spherical displays are reviewed.

Using 2D maps for geospatial visualization is a well studied area with a long history (Snyder, 1997). The main focus of map projection techniques is how to create a flat instance of the Earth while controlling and reducing map distortions.

Recently, perhaps due to easier perception, physical visualization of data has received more attention. Djavaherpour et.al (Djavaherpour et al., 2017) created a physical model of Digital Earth and provided several printed datasets that can be attached or detached on top of the physical model to study and for educational purposes. The main limitation of this work is how to use it for live and dynamic datasets.

Our work is primarily relevant to the visualization of Digital Earth datasets, which use a virtual 3D globe as the medium (Mahdavi-Amiri et al., 2015a). Vega et.al (Vega et al., 2014) present the main challenges and benefits of geospatial visualization on a spherical display. They discussed the benefits of spherical displays installations including educational applications. National Oceanic and Atmospheric Administration "NOAA" (NOAA, 2014) designed a system called "SOS" or Science On a Sphere (Schollaert Uz et al., 2014; SOS, 2004), which is a room sized global display system that projects four high resolution videos onto a six foot diameter sphere. The set up is designed to project videos from outside the globe, and the projection is spherical which may cause misconception of area and positions. Also, there are other commercialized large spherical displays such as Ominisphere (Murphy, 2009) and Hard-Ball (Vega et al., 2014).

Generally, in these works, spherical mapping is used to wrap 2D input images/videos on the spherical displays. However, there is extreme distortion when we use spherical mapping (particularly near the North pole and the South pole), and wrap 2D images on 3D displays. There is a large list of map-projection techniques for reducing or controlling the resulting distortion (Snyder, 1997). When we map a flat 2D im-

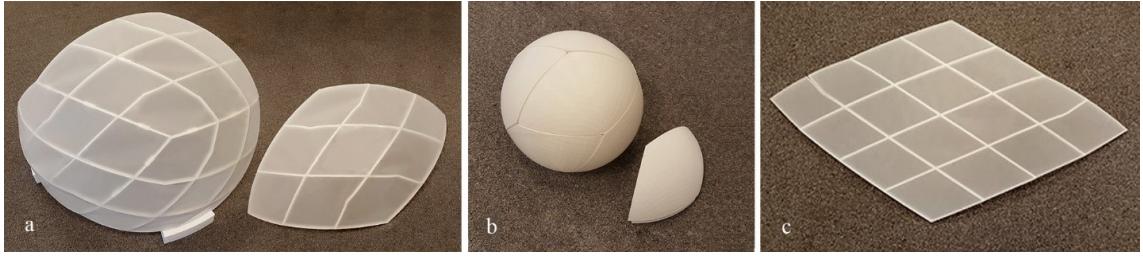


Figure 4: Various sizes and resolutions of cell-panels. (a) Resolution zero, final globe with 1 meter diameter and cell-panel size around 50×50 . (b) Resolution zero, final globe with 20 centimetre diameter and cell-panel around 11×11 . (c) Resolution 2, final globe more than 8 meter diameter and cell-panel size around 60×60 .

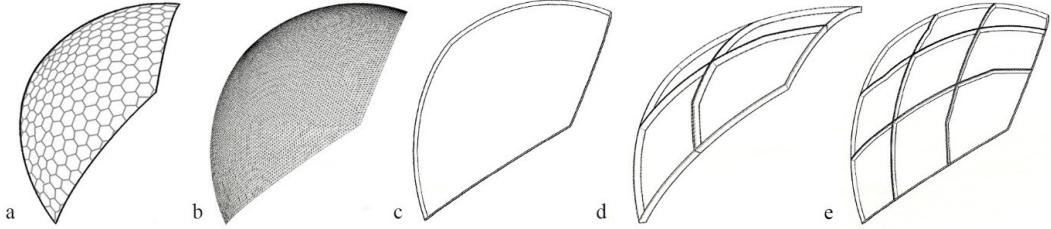


Figure 5: (a) DGGS hexagonal gridding model. (b) Imported mesh from DGGS. (c) Designed a frame based on DGGS mesh. (d) Designing two by two structure inside the frame to enhance curvature. (e) Designing three by three structure inside the frame to better approximate curvature.

age onto a curved surface, some amount of distortion (e.g. area, direction, shape) is unavoidable (Snyder, 1997; Gruen, 2012; Sahr et al., 2003; Peterson, 2006). Depending on the application, the particular mapping may be used. For example, the famous Mercator map projection preserves the direction and therefore it is good when the main purpose of the map is navigation. However, area is extremely distorted in this type of map, greatly expanding areas near the pole relative to areas near the equator. Alternatively, map projections such as Azimuthal area preserving works well for the purpose of analysis when making comparisons between sizes of areas on the map.

One approach to reducing distortion is to employ multiple 2D domains instead of a single domain. For example, one can better approximate the sphere with a cube (six flat 2D domains) instead of only one single plane. Certainly this can be extended providing even better approximations if we use a spherical polyhedron with more cells than the cube model (Snyder, 1992; Mahdavi-Amiri et al., 2015a). Discrete Grid Globe Systems use an initial polyhedron for approximating the Earth’s surface. DGGS are considered as a “*distributed global information system*” that provides an on the fly integration of geospatial datasets (Purss et al., 2016). HEALPIX (Gorski et al., 2005), SCENZGrid (SCENZGrid, 2010), HSDS (Goodchild and Shireen, 1992) and Pyxis’ Digital Earth (Peterson, 2006) are examples of DGGS.

Although, we have used Pyxis system for this

work, our methodology is general and independent from underlying DGGS.

3 METHODOLOGY

The goal of this paper is to provide the means for presenting dynamic visualization of geospatial data on a curved-display. We use Pyxis’ DGGS (Peterson, 2006) for discretizing the Earth into several rhombus cells. The cells of Pyxis DGGS are based on hexagons and higher resolution cells are constructed through a 1-to-3 refinement (Mahdavi-Amiri et al., 2015a). The initial polyhedron is a truncated icosahedron (see Figure 2). However, for the purpose of inter-operability and data transmission a collection of hexagonal cells are transformed to rhombuses, using grid conversion (Mahdavi-Amiri et al., 2016). The resulting rhombuses are also hierarchical. The first resolution (i.e., resolution zero) is constructed from a spherical icosahedron where each rhombus is a pair of triangles (see Figure 3 Left). The refinement for creating the multiresolution is a 1-to-9 refinement (Mahdavi-Amiri et al., 2015a) (see Figure 3 Right) (i.e. a 3D mesh).

Using Pyxis DGGS (Peterson, 2006), we can create the geometry of the cell and also have access to geospatial data associated with that cell. Therefore, if we build our curved-display based on the rhombus cells, we will have access to a huge amount of data in-

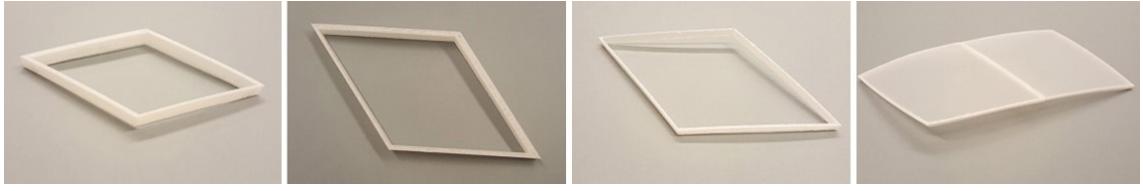


Figure 6: Different thickness tested when designing the frame of the cell-panels.



Figure 7: When cell-panels are too large, the projection paper is not able to smoothly adapt to the cell's curvature.

cluding dynamic sets, that can be mapped accurately to the corresponding rhombus on the display.

3.1 Curved-Display Screen

We built our curved-display through 3D printing. We fabricated a piecewise display where each piece corresponds to a DGGS cell at a specific resolution. We call these printed pieces *cell-panels*. For printing these cell-panels, we need to first determine the size and resolution of the physical globe. The size and resolution of the globe defines the display cell-panel size. For example, if we use the resolution zero, ten cells will cover the entire globe (See Figure 3, left). To produce a globe with one meter diameter, the size of the cell-panels is around 50×50 centimetres (Figure 4-a), whereas for a globe with a 20 centimetre diameter, the size of the cell-panel would be 11×11 centimetres (Figure 4-b). For a globe with an eight meter diameter, the cell size at resolution two (810 cells) is approximately 60×60 centimetres (Figure 4-c).

For our installation, we chose a one-meter diameter for the entire globe at resolution zero. Consequently, our final display made up of cell-panels, each sized at 50×50 centimetres. When fabricating each cell-panel, we use Pyxis Digital Earth to export the geometry of the cell as a 3D mesh (Figure 5 a, b). We only print edges of each cell (Figure 5 c), and in order to make these cell-panels work as screen we will obtain better image quality if they are covered in a proper rear-projection screen material. The projection paper is glued onto the 3D printed frame.

When designing the frame we tested several thicknesses as shown in Figure 6. To minimize shadows and seams in the image, it is optimal to keep these frames as thin as possible. With our PLA printing material we found that two millimeters was sufficient

to provide strength and durability with minimal thickness.

As is shown in Figure 7 our cell-panel size of approximately 50×50 centimeters has too much curvature over the surface of the rhombus to be covered smoothly with the rear projection paper. Consequently we created an internal structure to support and guide the paper. First, we tested a two by two internal structure (Figure 5, d) and after covering it with paper we observed that the problem still exists. In the next iteration, we tested using three by three elements as the internal structure (Figure 5, e) and the result was acceptably smooth. Figure 8, (a,c) shows the final result. We also designed and printed clips for connecting cell-panels as well as stands for stabilizing and orienting the final curved-display (Figure 8 b,d).

For fabricating these cell-panels, we have used the MakerGear M2 desktop 3D printer. Each internal structure unit takes around 2 hours to print and uses less than 2-meters of clear-filament (USA, 2014).

3.2 Projector Setup

To setup projector devices, we could either use rear or front projection. The problem with front projection is the shadows of viewers on the globe. Therefore, we decided to use rear projection. We have done our experiments with three projector devices available in our lab. Each projector can feed one, two or more panels. This panel per projector factor, P can be determined according to the size of the display and also the projector specs (i.e. brightness, image size and throw ratio). Our small projector¹ can easily feed two 50×50 display panels. Figure 9 shows different projector setups which we have experimented.

We put each projector in front of its cell-panel in a way that the center of each projector was perpendicular to the center of its cell-panel (see Figure 1).

3.3 Projector controller

Naturally, if we point a projector at a piecewise curved surface, we will have to carefully adjust the

¹Dell: M110 Ultra-Portable Projector HDMI 1280x800 300 ANSI Lumens 10000:1.

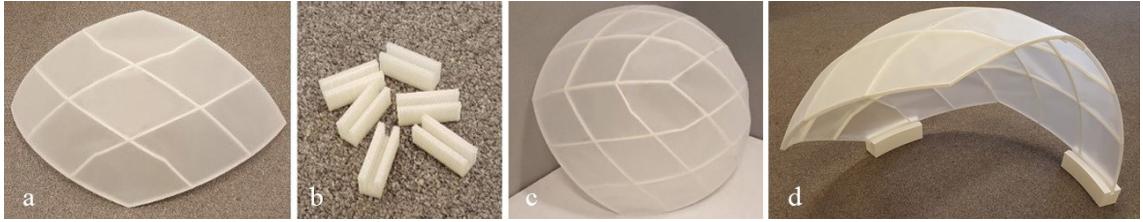


Figure 8: (a) Cell-panel with a three by three internal structure, covered with paper (b) Clips for attaching cell-panels (c) Final curved-display after attaching cell-panels. (d) Final display surface with a stand.

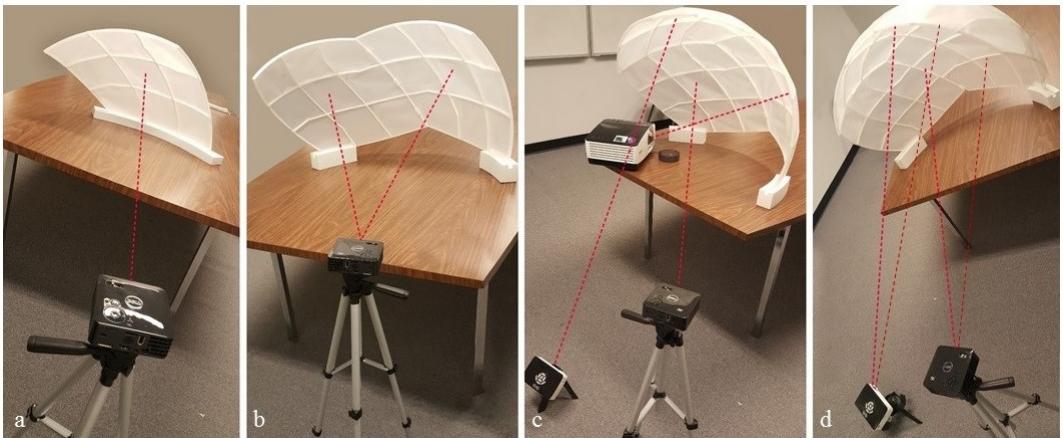


Figure 9: Different projector / panel setups. (a) One projector on one panel covering 10% of the globe. (b) One projector on two panels covering 20% of the globe. (c) Three projectors on three panels covering 30% of the globe. (d) Two projectors on four panels covering 40% of the globe.

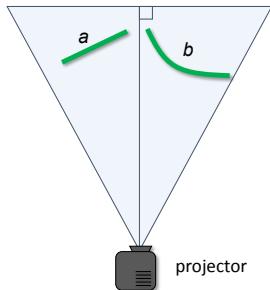


Figure 10: Projecting onto an angled (a) or curved (b) surface will cause the projected imagery to appear distorted.

image sent by the projector in order to be sure it is aligned with the surface and that, particularly because these surfaces are curved and often not perpendicular to the projector's beam (Figure 10). The projector controller software that accomplishes this was written in WebGL. The remainder of this section describes techniques which this software uses to adjust the image.

To prevent distortion, we use the geometry of curved cells (i.e. rhombus), as well as measurements of the projector's projection to adjust the imagery

(representing the data associated to the cell) before it is projected. So that it will be positioned correctly on the model. Sending the image without any wrapping to compensate the curvature of the display, to the projector device could create extreme distortion on the curved display. Therefore, we first need to warp the image to cancel out the curvature of the display. The geometry of the cell's 3D model is the main tool for finding the warp. To do this, we exactly recreate our cell's 3D model as well as the projector's perspective projection and the relative positions and orientations of these two objects in a 3D rendering environment (in our case, OpenGL). The rendered 2D image will then, once projected onto the model, display the imagery correctly on the surface of the cell's 3D model.

3.3.1 Modelling the Projection

We start from the assumption that our projector casts imagery along a frustum. This may not precisely be the case, particularly when at short distances from short throw projectors utilizing wide angle lenses, but in our experience it has been close enough to approximately match the display surface well.

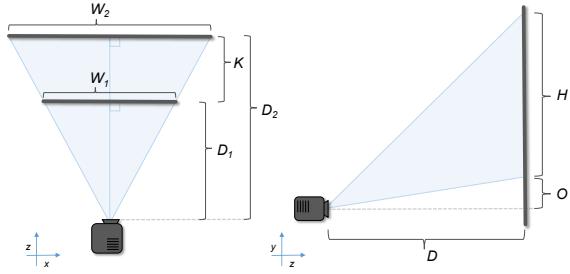


Figure 11: Top-down and side views of measuring a projector’s projection parameters.

To recreate this frustum within a virtual environment we need to identify the projector’s projection parameters. We do this by measuring points on its frustum. Ultimately, given that we work within OpenGL, we need the following parameters: near plane top n_t , near plane bottom n_b , near plane left n_l , near plane right n_r , and the near plane distance D_n from the center of projection. We assume that the center of the projection is the origin of our coordinate space.

To find these parameters we first ensure the projector is level perpendicular to a flat surface. We measure the distance from the front of the projector to the surface D_1 and the width W_1 and height H_1 . The projectors we used cast their image above the projector so we also measured the offset between an imaginary vector perpendicular from the projector to the wall and the bottom of the image O_1 (Figure 11). Then we move the projector further from the wall and measure these parameters again (D_2, W_2, H_2, O_2) , $D_2 > D_1$.

The main challenge at this point is that we do not know the distance of each of these two planes from the center of projection as this distance (let’s label these d_1 and d_2) will be somewhat different than D_1 , and D_2 as within the projector neither the lens nor its light source provide a clear singular, measurable central point of projection.

So, we can calculate d_1 and d_2 using similar triangles. That is, if we let $k = D_2 - D_1 = d_2 - d_1$ (Figure 11) then:

$$\frac{W_1}{d_1} = \frac{W_2}{d_2} = \frac{W_2}{(d_1 + k)}$$

and solving for d_1 yields: $d_1 = \frac{kW_1}{(W_2 - W_1)}$ and $d_2 = d_1 + k$.

When measuring, we choose D_1 and D_2 as relatively large and far from the projector (i.e., 1-2 metres) so our measurements would be as accurate as possible. However in our virtual setting we want d_n to be much smaller than D_1 to avoid potential near clipping in the 3D scene and so we chose a value roughly $d_n = \frac{1}{10}D_1$. With a value for d_n picked then by similar triangles the near width W_n , near height H_n , and near

offset O_n are:

$$W_n = \frac{d_n W_1}{d_1} H_n = \frac{d_n H_1}{d_1} O_n = \frac{d_n O_1}{d_1}.$$

So the frustum is defined by

$$(n_l, n_r, n_b, n_t, d_n) = (-W_n/2, W_n/2, O_n, O_n + H_n, d_n).$$

As we make use of three projectors, one for each tile, if the projectors are different models, the above parameters will have to be measured and calculated separately for each projector.

3.3.2 Aligning the Virtual and Physical Models

The remaining challenge is to place the virtual surface model in OpenGL to match the alignment of the projector and the cell-panel in the real world. In our set-up, to minimize shadows created by the frame within the Earth surface model we aim to place cell-panel so that the center of each rhombus is as close as possible to being orthogonal to the center of projection. Consequently, our initial alignment in the virtual environment is orthogonal to the center of projection.

Our software interface provides translation, scaling as well as yaw, pitch, and roll controls to adjust the virtual environment until a good match is found with the physical environment.

Our alignment procedure is to place the physical model and projectors such that the projected image covers the entire rhombus and that the path between the projector and cell-panel is not obscured by the other projectors. Then the virtual model is adjusted; first scale, translation, and roll so that the corners of the projected imagery roughly align with the corners of the cell-panel. Then pitch and yaw are modified to exactly align the virtual shape with the physical. Often some final fine-tuning of the scale and translation will be necessary to complete the alignment. This procedure is independently repeated for each projector and corresponding rhombus.

4 RESULTS AND DISCUSSION

As proof of concept, we have created several set-ups, each with multiple cell-panels. After fabricating each cell-panel, we set up our curved-display and projectors; for displaying our static and dynamic datasets on each cell-panel. In each setup, we may need to attach cell-panels (using clips see Figure 8, b). Then, using the projector controller software, we align the projected image with each cell panel. This normally takes less than five minutes for each configuration (see Figure 9). Notice that the first time setup may

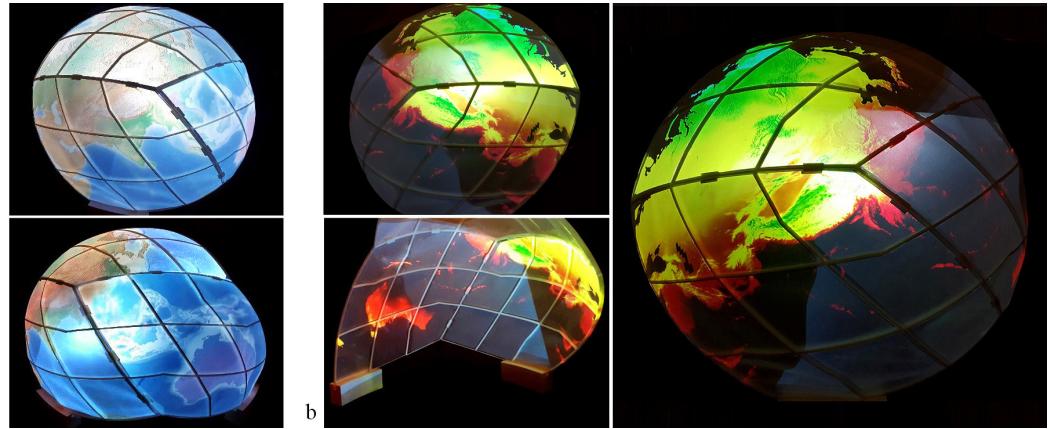


Figure 12: Representing various static and dynamic data sets on curved-display. (a) Elevation data. (b) global temperature from 2015 to 2050.

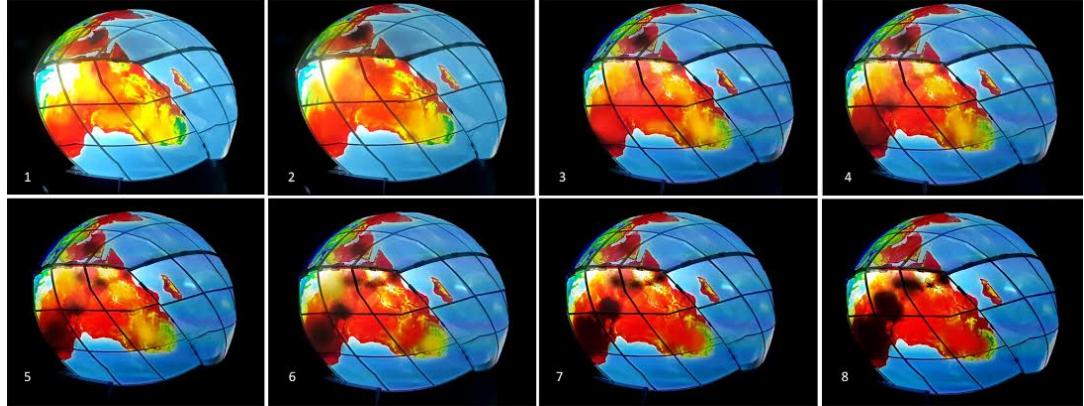


Figure 13: Animation of dynamic visualization of Global temperature from 2015 to 2050 for Africa.

take longer as determining the relative positions of projectors and cell-panels usually needs some trial and error.

Our first results are from a setup of three projectors and three panels (see Figure 9, c). Using this setup we visualize a static dataset of elevation data shown in Figure 12 a,. Also, a dynamic dataset (i.e. the global temperature change from 2015 to 2050) (Pyxis, 2017) is presented in Figure 12 b. In Figure 12 b, we have tried to capture details of the setup from both outside and inside the curved-display. This particular dataset is useful in examining potential climate change effects and together with our display installation allows an analyst (or a group of 3 – 4 analysts) to study this dataset over 30% of the Earth’s surface.

Obviously, we can use each individual panel for display dataset for each rhombus cell which covers 10% of the globe. Figure 13 shows the animation that presents dynamic visualization of global warming frame by frame on one panel for Africa. This is proof of the concept that the introduced framework

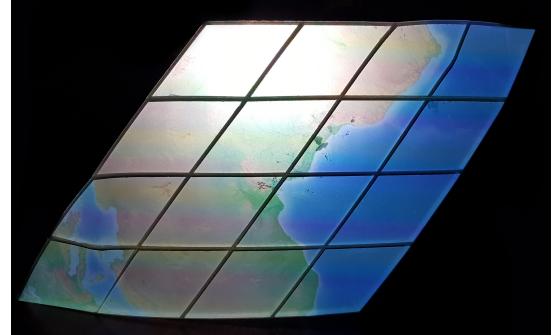


Figure 14: Data projection on one cell in resolution one, showing elevation dataset.

is useful for dynamic data visualization on curved-displays.

Our second setup is two projectors and four cell-panels (Figure 9, d). With this setup we can project a dynamic geospatial dataset on 40% of the globe using two projectors. This setup can be extended to five projectors and ten panels and cover the whole globe.

We have used this setup to visualize the global precipitation change (see supplementary video).

Further, we have fabricated cell-panels for larger globe. Figure 14, shows the results of projecting data on a cell-panel at resolution 2 (see Figure 2). This cell presents 1/90 of the entire Earth. As it is shown in this figure, the panel is more flat than the cells in resolution zero.



Figure 15: Using the piecewise nature of our framework, we can compare India and Brazil side by side.

Using our cell-based approach, it is possible to compare far regions of the globe (e.g. Brazil and India) side by side (see Figure 15). However, this comparison is tedious for spherical displays such as SOS (SOS, 2004).



Figure 16: Visualizing earthquake incidents in Brazil and Greenland on the world 2D Google map.

As mentioned in the Introduction, one of the unique features of our method is the use of area preserving projection. Projecting from the surface of the Earth to 2D maps could create extreme area distortion. Figure 16 shows an example of Mercator maps used in common map software. In this Figure, Greenland and Brazil are highlighted. Although in this map Brazil seems smaller than Greenland, in reality it is four times larger than this island (see Figure 17).

This area distortion creates misinterpretation and potentially wrong visual analysis. For example if we

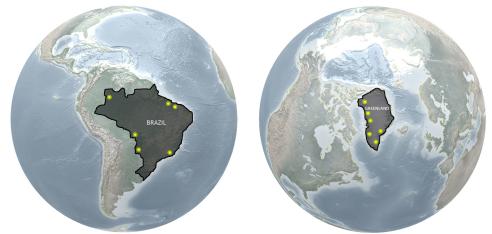


Figure 17: Visualizing earthquake incidents in Brazil and Greenland on a digital model of the globe from Pyxis World View Studio.



Figure 18: projecting Brazil and Greenland on the curved display with more realistic sizes. Earthquake incidents visualizations have been

visualize the number and locations of recent earthquakes, it seems, that Greenland has a lower risk of earthquakes, which is not correct. Figure 18 shows the visualization of earthquake incidents in Greenland and Brazil projected on one of our setups.

5 CONCLUSION AND FUTURE WORKS

In this paper we introduced a DIY method for creating physical globe a a curved-display for projecting geospatial dataset. Our method is flexible and relies on off-the-shelf tools with easy installation process. We employ DGGs (Pyxis) for decomposing the Earth to the uniformly sized cells. This system is also used for access many geospatial datasets. Finally, we developed a projector controller that takes the geometry and data of cells and adjusts it for the projector.

There are several directions to extend this work. One natural direction is to create a setup for entire globe. Also, improving the design of cell-panels such that the shadow effect could be reduced.

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REFERENCES

- Djavaherpour, H., Mahdavi-Amiri, A., and Samavati, F. F. (2017). Physical visualization of geospatial datasets. *IEEE Computer Graphics and Applications*, 38(3):61–69.
- Goodchild, M. F. and Shiren, Y. (1992). A hierarchical spatial data structure for global geographic information systems. *CVGIP: Graphical Models and Image Processing*, 54(1):31–44.
- Gorski, K. M., Hivon, E., Banday, A., Wandelt, B. D., Hansen, F. K., Reinecke, M., and Bartelmann, M. (2005). Healpix: a framework for high-resolution discretization and fast analysis of data distributed on the sphere. *The Astrophysical Journal*, 622(2):759.
- Grafarend, E. (1995). The optimal universal transverse mercator projection. In *Geodetic Theory Today*, pages 51–51. Springer.
- Gruen, A. (2012). Satellite versus aerial images—not always a matter of choice. *GEOInformatics, The Netherlands*, 15:44.
- Hruby, F., Kristen, J., and Riedl, A. (2008). Global stories on tactile hyperglobes—visualizing global change research for global change actors. *Proceedings, Digital Earth Summit on Geoinformatics: Tools for Global Change Research, Potsdam, Germany*.
- Mahdavi-Amiri, A., Alderson, T., and Samavati, F. (2015a). A survey of digital earth. *Computers & Graphics*, 53, Part B:95 – 117.
- Mahdavi-Amiri, A., Harrison, E., and Samavati, F. (2016). Hierarchical grid conversion. *Computer-Aided Design*, 79:12 – 26.
- Mahdavi-Amiri, A., Samavati, F., and Peterson, P. (2015b). Categorization and conversions for indexing methods of discrete global grid systems. *ISPRS International Journal of Geo-Information*, 4(1):320–336.
- Meng, L. (2003). Missing theories and methods in digital cartography. In *21st International Cartographic Conference*, pages 1887–18.
- Murphy, D. (2009). Software: Omnisphere. *ID (New York, NY)*, 56(3):87.
- NOAA (2014). National oceanic and atmospheric administration. <http://www.noaa.gov/>.
- Peterson, P. (2006). Close-packed, uniformly adjacent, multiresolutional, overlapping spatial data ordering. <http://www.google.com/patents/EP1654707A1?cl=en>. EP Patent App. EP20040761671.
- Purss, M. B., Gibb, R., Samavati, F., Peterson, P., and Ben, J. (2016). The ogc® discrete global grid system core standard: A framework for rapid geospatial integration. <http://www.opengeospatial.org/projects/groups/dggsswg>.
- Pyxis (2017). the pyxis innovation inc. <https://www.pyxisinnovation.com/Products/Studio>.
- Randall, D. A., Ringler, T. D., Heikes, R. P., Jones, P., and Baumgardner, J. (2002). Climate modeling with spherical geodesic grids. *Computing in Science & Engineering*, 4(5):32–41.
- Sahr, K., White, D., and Kimerling, A. J. (2003). Geodesic discrete global grid systems. *Cartography and Geographic Information Science*, 30(2):121–134.
- SCENZGrid (2010). Solid earth and environment grid. <https://www.seagrid.csiro.au/wiki/SCENZGrid/WebHome>.
- Schollaert Uz, S., Ackerman, W., O’Leary, J., Culbertson, B., Rowley, P., and Arkin, P. A. (2014). The effectiveness of science on a sphere stories to improve climate literacy among the general public. *Journal of Geoscience Education*, 62(3):485–494.
- Sherlock, M., Hasan, M., and Samavati, F. (2016). Interactive data styling and multifocal visualization for a view-aware digital earth. Technical report, University of Calgary.
- Snyder, J. P. (1992). An equal-area map projection for polyhedral globes. *Cartographica: The International Journal for Geographic Information and Geovisualization*, 29(1):10–21.
- Snyder, J. P. (1997). *Flattening the earth: two thousand years of map projections*. University of Chicago Press.
- SOS (2004). Science on a Sphere. <https://sos.noaa.gov/What-is-SOS/>.
- USA, B. (2014). Bumat clear pla filament 1.75mm / 2.2 lbs. <http://www.bumatusa.com/products/bumat-clear-pla-filament-1-75mm-2-2-lbs/>.
- Vega, K., Wernert, E., Beard, P., Gniady, C., Reagan, D., Boyles, M., and Eller, C. (2014). Visualization on spherical displays: Challenges and opportunities. *Proceedings of the IEEE VIS Arts Program (VISAP)*, pages 108–116.
- Xie, J., Yu, H., and Ma, K.-L. (2013). Interactive ray casting of geodesic grids. In *Computer Graphics Forum*, volume 32, pages 481–490. Wiley Online Library.
- Zolfaghari, E. (2014). Why every world map you’re looking at is wrong: Africa, china and india are distorted despite access to accurate satellite data.